

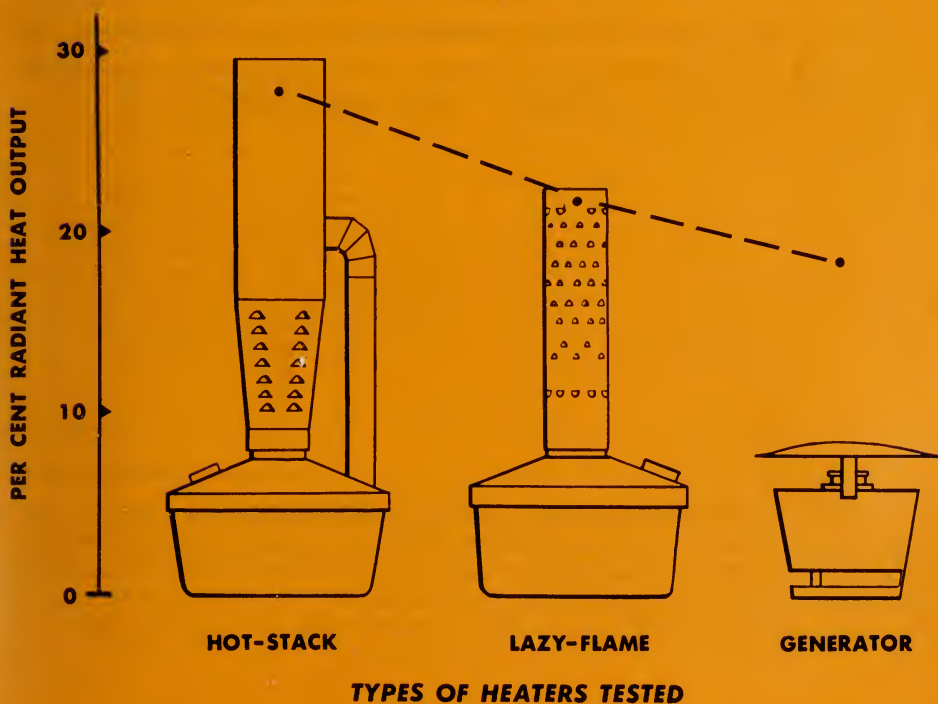
EFFECTIVENESS OF ORCHARD HEATERS

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Orchard heaters

have been used as a means of protection from frost for many years, but there is still much to be learned about the actual process of heating an orchard, and the effects of the many factors involved. Heating practices vary considerably, and the relative effectiveness of different types of heaters has long been a source of argument.

This bulletin

reports in detail the methods used and the results obtained during orchard heating studies made by the Agricultural Engineering Division of the University of California's College of Agriculture. The chief objectives were to obtain a better understanding of the heat-transfer processes involved in heating an orchard and to investigate possible differences in effectiveness of various types of heaters.

These studies were made in citrus orchards in southern California, during the five winters from 1937 to 1942. Although no detailed tests have been made in deciduous orchards, the principles discussed in this bulletin should still be applicable.

This is not a report on the wind machine research project currently being conducted, although this phase of the frost protection studies is mentioned briefly.

Since the studies reported herein were rather complex, the description and the tabulation of results is rather detailed and somewhat technical. A resume of this information, edited for easier reading, may be found in California Experiment Station Circular 400, "Principles of Orchard Heating," by the same author. Observations and experiences in the **operation** of heaters, obtained concurrently with the results reported herein, may be found in California Experiment Station Bulletin 643, "Operation of Orchard Heaters," also by the same author.

In order that the information in our publications may be more intelligible it is sometimes necessary to use trade names of products or equipment rather than complicated descriptive or chemical identifications. In so doing it is unavoidable in some cases that similar products which are on the market under other trade names may not be cited. No endorsement of named products is intended nor is criticism implied of similar products which are not mentioned.

Effectiveness of Orchard Heaters

Robert A. Kepner

The studies involved nine kinds of heaters,
and several different sizes of orchards

DURING 5 winters of field tests at the University of California Citrus Experiment Station at Riverside, comprehensive studies of 9 different kinds of heaters were conducted in a one-acre heated portion of a large orchard. An extensive network of thermocouples* was used to automatically record temperatures at various locations in both heated and unheated plots. Soil temperatures were measured to a depth of 12 inches below the ground surface and air temperatures to a height of 60 feet above the ground. On several occasions, a captive balloon was used to obtain temperature and humidity data up to heights of 300 feet or more. Other environmental factors, such as wind, atmospheric radiation, and heat flow from the soil were evaluated during the tests.

On 5 occasions during this period, isolated areas ranging in size from 7 to 28 acres were instrumented with portable

equipment, so that heating studies could be made. One such test was at Porterville on a night when heavy firing was required, 2 were at West Covina on nights when only light firing was needed, and 2 heating runs were made at Riverside under conditions which were typical for radiation frosts, but with temperatures not quite low enough to actually require protection.

Quantitative data were not obtained for mass heating conditions, partly because there were very few nights during the 5-year period when extensive firing was required, and partly because of the difficulty of obtaining reliable unheated check temperatures when an entire district is heated.

In addition to the field studies, laboratory tests of individual heaters were conducted at Davis to determine the thermal characteristics of several kinds of heaters at various burning rates. These tests included measurements of radiant energy output, metal temperatures at various locations on the stack and cover, oil temperatures in the bowl, and stack-gas temperatures and velocities. Only the radiant energy characteristics are discussed in this publication.

* A thermocouple is a junction between two wires of dissimilar metals which generates an electrical response that is measured with an appropriate instrument. By using small size wires, such as 20 or 24 gage, the thermocouple junction will follow air temperature changes closely and have negligible radiation error.

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Background information: a review of the fundamental methods of heat transfer

As an aid in understanding the rather complicated process of heating an orchard, the following paragraphs include a brief review of the fundamental modes of heat transmission; conduction, convection, and radiation. Heat transfer by any of these 3 methods depends upon a difference in temperature, and heat is always transmitted from the warmer to the cooler body.

Conduction is the transfer of heat from one part of a body to another part of the same body, or from one body to another in physical contact with it, without appreciable displacement of the particles of the body. For example, if one end of a rod is heated, the other end will soon become warmed due to conduction along the rod. In an orchard, the center of a fruit is warmed or cooled primarily by conduction of heat from or to the outside surface. Movement of heat within the soil is by conduction resulting from temperature differences that have been set up in the soil.

Convection is the transfer of heat from one point to another within a gas or liquid, by motion or mixing. In **natural convection**, the motion of the fluid is entirely the result of differences in density resulting from the differences in temperature. A floor furnace heats a room primarily by natural convection. The heated air, being lighter, rises to the ceiling, as denser air which has been cooled within the room settles to the floor. In **forced convection**, the motion of the fluid is primarily from an external source such as a heater fan in a room or a stirrer in water that is being heated or cooled. Wind, or a wind machine in an orchard produces forced convection.

Radiation is the transfer of heat through space from a hotter body to a colder body without the aid of intervening mediums. Radiation is transmitted without loss through evacuated space, and

with very little loss through dry air; but is *not* transmitted through most liquids. Other gases, such as carbon dioxide and water vapor, absorb at least part of the radiant energy.

Because radiant energy is transmitted through space only in straight lines, an object must "see" the source of radiant energy in order to receive heat from it directly. The greatest intensity of radiation is in a line perpendicular to the radiating surface.

A typical example of heat transfer by radiation is from a fireplace in a cold room. An occupant near the fire may be too warm on one side (because of the radiant energy received on that side) and yet be unpleasantly cold on the side away from the fire. A shield placed between the fireplace and the occupant would absorb or reflect much of the radiant energy, and the occupant would immediately feel cold on all sides.

It should not be inferred from the above example that an open flame is the most effective source of radiant energy. Heated bricks in the fireplace also contribute to the radiant energy in this case, and metal surfaces at high temperatures are an effective source of radiant energy. It will be shown in this report that the hot stacks of the combustion-chamber type of orchard heaters produce relatively more radiant energy than the colder stacks and open flames of lazy-flame heaters. This difference is apparent if one stands close to first one and then the other of these types of heaters. On a heating night the firing crew prefer to warm themselves by a Jumbo Cone heater for example, rather than by a lazy-flame type of heater.

In an orchard, leaves and fruit which are exposed to a heater will be warmed by direct radiation from the heater and may be a degree or two warmer than the surrounding air.

More background: the environmental conditions influencing heating requirements

Atmospheric radiation. Except for rather infrequent invasions of citrus districts by cold air at low levels from polar regions (the so-called “freezes”) most heating requirements occur as a result of nocturnal loss of heat by radiation to the cold sky. The air itself does not lose much heat by radiation, but becomes chilled mostly by contact with the cold ground or other exposed surfaces such as plant leaves, which are losing heat by radiation to the sky.

The net rate of heat loss by nocturnal radiation is influenced by the moisture content of the atmosphere and its temperature, particularly in the lower thousand feet or so. (The *overhead* air mass is almost always cold and dry during a frost.) Increasing the moisture content in the lower levels reduces the net radiation loss and tends to give steady conditions with a slow drop in temperature. On nights when the lower air is unusually dry (i.e., when there is low dew point*), the rate of radiation loss is large and orchard temperatures may be expected to drop rapidly.

Air temperature inversion. The air cooled by contact with chilled surfaces is more dense than the warmer air overhead and therefore remains close to the ground, becoming colder as the surface temperature of the earth continues to fall. This is just the reverse of daytime conditions, when the ground and other exposed surfaces are heated by the sun and in turn heat the lower air and cause it to rise. Thus the vertical gradient of temperature (relation of temperature to height) dur-

ing the night is an “inversion” of the daytime gradient. The size of the inversion on a quiet night is affected by the following factors: (a) the daytime temperature preceding the cold night, (b) the net rate of atmospheric radiation to the sky during the night, (c) the soil temperatures, and (d) the rate at which heat can be conducted to the soil surface from the lower depths.

In common orchard heating terminology, a condition of large inversion is referred to as a low ceiling, because the heated air and products of combustion from the heaters rise only a relatively short distance before encountering warm enough natural air temperatures to restrict their rising. Conversely, with a small inversion or high ceiling, the overhead air for a given orchard temperature is not as warm as with a large inversion, and products of combustion will rise higher.

Typical temperature inversion curves for two nights with different amounts of inversion are shown in figure 1. These curves show air temperatures up through the center of a space between trees in an orange orchard, as well as temperatures above bare plowed ground at a location 300 feet out from the edge of the orchard. At elevations above 20 feet, the temperatures were essentially the same in the two locations, but at the lower levels the orchard was several degrees colder than above the bare soil. In the orchard, the coldest air was at 2 to 5 feet elevation, while the air close to the ground was slightly warmer.

Above bare ground, the air is cooled only by coming in contact with the soil surface which in turn is being cooled by radiation to the sky. This air cannot become colder than the ground surface which is cooling it. In an orchard, the portions of trees exposed to the sky lose heat by radiation and in turn chill the air

* The dew point of a mixture of air and water vapor is the temperature at which condensation (dew, fog, etc.) would begin to occur if the mixture were cooled without change in composition. The more water vapor there is in the mixture, the higher will be the dew point or saturation temperature. Thus, the dew point is a measure of the amount of moisture present in the mixture.

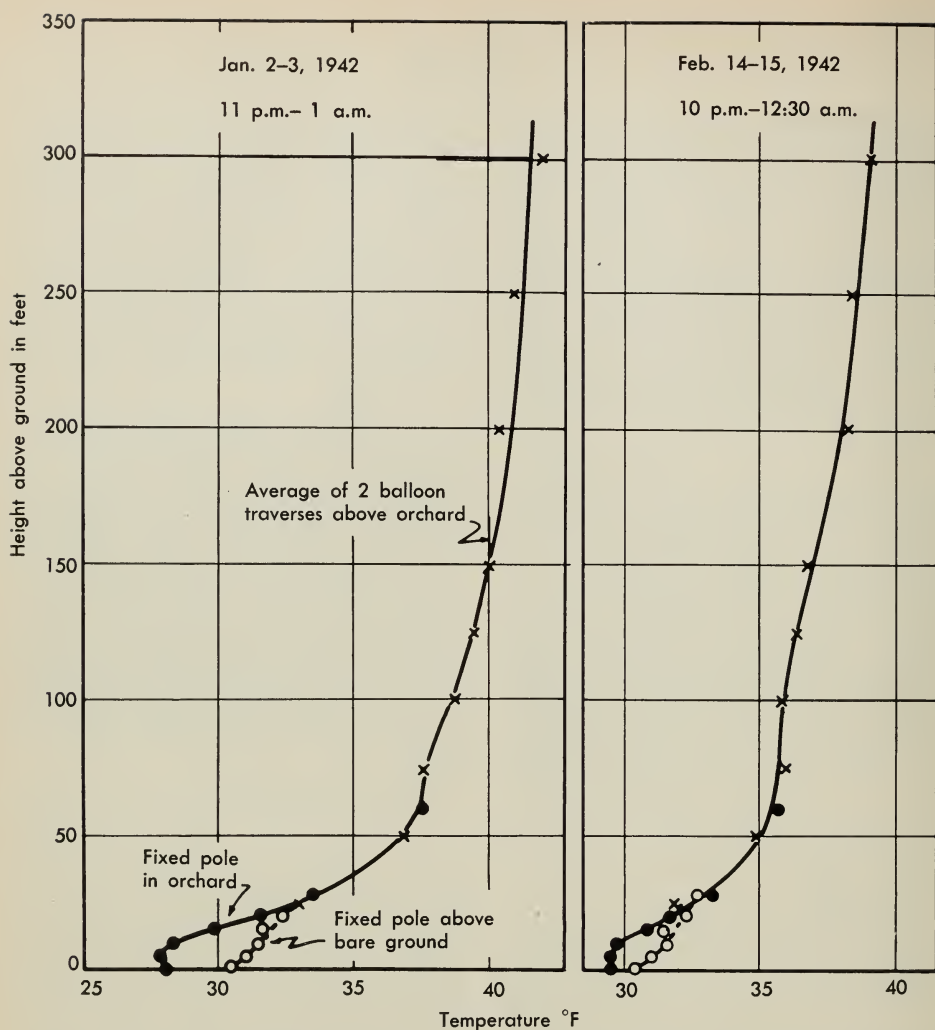


Fig. 1. Temperature profiles in orchard and above bare, plowed ground before lighting heaters, for two nights with different inversions. (Taken in and near 28-acre orchard at West Covina.)

which comes in contact with the foliage. Therefore, in an orchard, air cooling takes place throughout the entire height of the tree zone, and particularly at the tree tops. The foliage has a relatively low capacity for storing heat, and therefore cools rapidly by radiation, to a few degrees below air temperature. The soil, on the other hand, has a high heat capacity; heat stored in the lower levels of soil during the daytime is conducted to the surface during the night and in this way

retards the chilling of the top layer of soil.

The greater cooling of the foliage accounts for the lower air temperatures within the orchard as compared to those above bare ground. Within the orchard, the retarding effect of the subsoil heat causes the soil surface to be a little warmer than the air which has been cooled by the foliage. For example in the left-hand graph of figure 1, the average soil surface temperatures were probably between 29

and 30° F—colder than the air immediately above the bare field (since the soil was cooling this air), but warmer than the orchard air chilled by the trees.

Referring again to figure 1, note that the temperature increases rapidly with elevation within the lower 50 to 75 feet, and then increases more gradually up to the 300-foot limit of the readings. If the profiles were to be continued upward several hundred feet farther to a height above the influence of surface cooling, the upper portions of the curves would slope to the left due to the natural decrease of temperature with altitude.

In all following discussions, the differences between the 60-foot temperatures and the 5-foot tree-center air temperatures in the unheated plot are arbitrarily taken as a measure of the magnitude of the inversion. On this basis, the inversion indicated by the left-hand graph of figure 1 is about 9° F, while the right-hand curve shows about 6° F. These tests would represent conditions of moderately high ceiling, or a little less than average inversion.

Cold air drift. One of the major factors affecting the response from artificial heat, particularly in an isolated orchard, is air drift or air drainage. The air chilled by contact with the ground or foliage, being heavier than warmer air, will slowly flow downhill and underrun the warmer air. The filling of ground depressions by cold air from neighboring slopes increases the frost hazard in low spots. Conversely, the frost hazard is less on higher slopes where air drainage prevents the accumulation of chilled air. In the so-called "mass heating" of large areas, the air-drift effect diminishes except for border orchards.

Even on nearly flat terrain, and with a relatively quiet night, the air drift across an orchard may have a velocity of 1 to 2 miles per hour at a 20-foot elevation. (Velocities within the tree zone will be perhaps one third as great as those at 20 feet.) For several heating runs at Riverside, the amount of heat added to the in-

coming air was calculated by air layers, based upon the temperature increase and measured wind velocity for each layer.

On two of these nights, a 15-acre area was heated, with an average fuel input of about 34 gallons per acre per hour, and a wind velocity of 1½ to 2 miles per hour at the 20-foot elevation. On one of these two nights, when the inversion was 7.5° F, 80 per cent of the total heat available from the oil being burned in the entire upwind half of the area was needed to heat the incoming air, with 64 per cent of the total going into the air which entered the orchard above the 20-foot elevation and only 16 per cent being used to heat air entering below 20 feet. On the other night, the inversion was larger (14° F) and less heat went into the overhead air. The totals that night were 39 per cent into the air above 20 feet, and 28 per cent into the air below 20 feet.

These examples demonstrate the importance of air drift in determining heating requirements for isolated areas, and show the improved usage of heat with the larger inversion. They also suggest the importance of border heaters, which is discussed in more detail in a section starting on page 27.

Wind. While air drift increases the heating requirements, it is a common observation that when the wind velocity becomes great enough, the lower layers of air are warmed by mixing with the warmer air above. Such a wind may greatly reduce the inversion and boost orchard temperatures above the danger point within a period of a few minutes. In the field laboratory at the Citrus Experiment Station at Riverside, this effect became noticeable whenever the wind velocity at the 20-foot elevation exceeded about 2½ miles per hour—a condition which would barely rustle the tree leaves. If, however, there is little or no inversion, wind will increase heating requirements.

The soil as a source of heat: For the usual atmospheric conditions during radiation frosts, the net loss of heat to

the cold sky by radiation is about 20 Btu* per hour, per square foot of area, or about 900,000 Btu per hour, per acre.† This loss is equivalent to the perfect utilization of the heat of combustion from 6½ gallons of oil per hour per acre.

In an unheated area, the ground is the main source of the heat lost by radiation. As the ground surface is cooled to below the daily mean temperature, heat is conducted up from the warmer soil at the lower levels. Any practice, therefore, which increases the soil thermal conductivity will improve the availability of the soil heat, and also increase the flow of heat into the soil during the daytime. Covering or loosening the soil surface is detrimental to heat transfer, while increasing the moisture content is beneficial. However, if a frost occurs within a few days after an irrigation, evaporative cooling from the wet soil surface may more than offset the advantage of the increased thermal conductivity.

Typical relative temperatures at various soil depths and in the air just above the soil are indicated in table 1.

The temperatures in table 1 are averages for 7 nights during January and early February at Riverside, with moderate inversions. Each temperature was recorded electrically at 10-minute intervals and averaged for the period from about midnight to 3 a.m. Note that near the surface the soil under the tree is considerably warmer than the soil between trees. This is because the tree shields its soil from direct radiation to the sky. The *air* beneath the tree is nearly as cold as in the space, because it is being cooled by the leaves and because of air mixing due to drift and convection currents. At the center of the tree space the soil is considerably colder at the surface than at the 12-inch depth. It is this temperature difference that causes heat to flow from the lower layers of soil to the surface during the night.

Response is related to heater characteristics and placement in the orchard

The output from heaters in an orchard is available partly as convective heat (products of combustion and air heated by contact with the stacks) and partly as radiant energy from the flame or from hot metal surfaces. Some of the factors which influence the effectiveness of the convective heat are (a) the amount of temperature inversion on a particular night, (b) the velocity and temperature of the products of combustion as they leave the stack, (c) the height above ground at which the stack gases are discharged, (d) the size of individual fires

or volume of the products of combustion from each heater, (e) the wind velocity and the resultant mixing action, and (f) the distance in from the edge of the heated area. In general, the inversion is the most important of the above factors. The smaller the inversion, the greater is the loss of convective heat above the tree tops.

Since radiant energy can be transmitted between objects without heating the intervening air, this type of heat becomes most important when the inversion is small and convective heat is not very effective. It is also important in border heating because with proper placing of heaters, the radiant energy received by the trees and fruit can result in their temperature being several degrees above that of the surrounding air.

* One Btu (British thermal unit) is the quantity of heat required to raise the temperature of one pound of water one degree Fahrenheit.

† Schoonover, Warren R., F. A. Brooks, and H. B. Walker. Protection of orchards against frost. Calif. Agr. Ext. Cir. 111: 1-70. 1939.

Table 1.—Relative Temperatures at Various Soil Depths and In the Air Above the Soil

	Unheated temperatures, ° F.	
	in or under tree center	at center of tree space
Air temp. 5 ft. above ground.....	34.1	33.8
Air temp. 3 in. above ground.....	34.9	33.9
Soil surface temp.....	45.8	36.7
Soil temp., 2 in. below surface.....	48.5	41.7
Soil temp., 6 in. below surface.....	51.4	47.8
Soil temp., 12 in. below surface.....	52.6	50.7

Radiant energy from heaters. In considering the effect of the radiant energy which a heater develops, it is necessary to determine both the total radiant output, and the distribution of this output in relation to vertical angle. This was accomplished in the laboratories at Davis



Fig. 2. Laboratory set-up for determining the thermal characteristics of heaters, at Davis.

by mounting each heater about 10 feet above the floor as shown in figure 2, so that radiation readings could be made from various angles in a vertical plane all the way around the heater. From these readings it was possible to calculate for each test run the "radiant fraction" (defined as the amount of radiant energy put out by the heater, divided by the total energy available from perfect combustion of the fuel, and expressed as a percentage).

Figure 3 shows curves of total radiant fraction vs. burning rate, for several kinds of heaters. For most of these heaters, the radiant fraction tends to remain about constant regardless of burning rate, especially at the higher rates.

Only a portion of the total radiant energy from the heaters strikes the trees. The remainder goes either to the ground or to the sky. The amount which is intercepted by the trees depends upon the size and spacing of the trees, and the location of the heaters with respect to the trees. The energy radiated to the sky is practically wasted insofar as orchard heating is concerned. The heat radiated to the ground is partially effective, since it results in additional heating of the air in contact with the warmed soil. However, this heat is rather localized around the heater and much of it goes below the top levels of the soil.

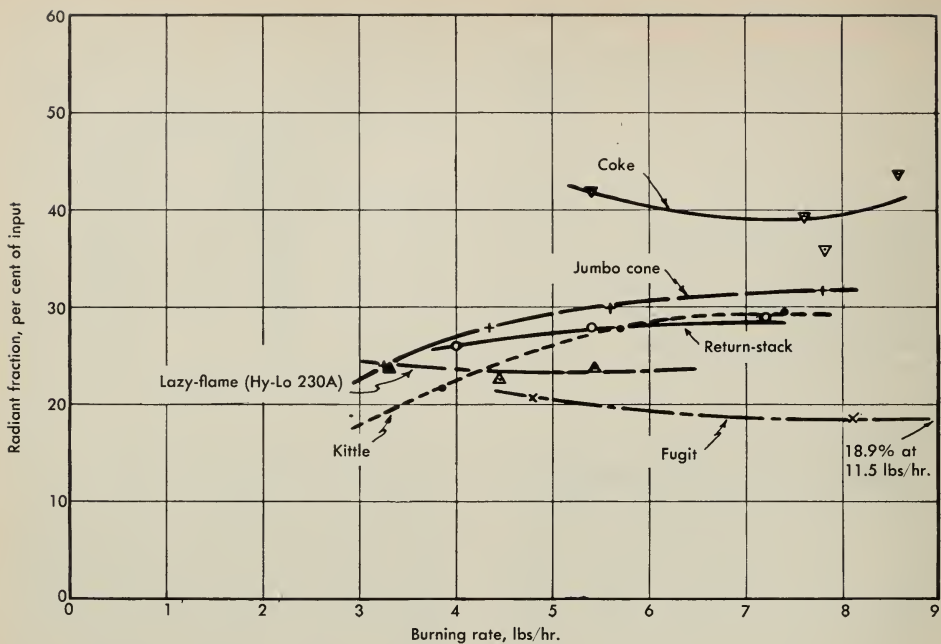


Fig. 3. This graph shows the relation between burning rate and the total radiant fraction from the heaters. Results are included for six different kinds of heaters.

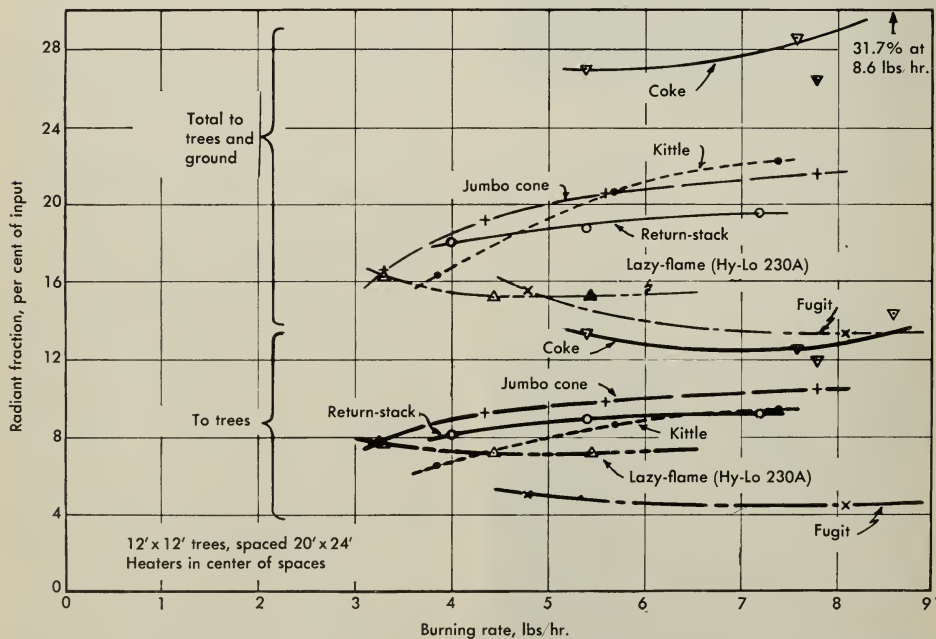


Fig. 4. This graph shows radiant fractions transmitted from various kinds of heaters to the trees only, and also the total to the trees and ground.

The radiant fractions transmitted to trees of the size and spacing encountered at Riverside are shown by the group of heavy curves in the lower part of figure 4. The upper curves indicate the total energy radiated to the trees and ground combined. Table 2 summarizes the radiant fractions from the various kinds of heaters and the distribution of radiant energy for two sizes of trees.

In general, with trees 12 feet in diameter and 12 feet high, the division of radiant energy between the ground, trees and sky is about equal. Larger trees intercept additional amounts of radiation which would otherwise be lost to the sky. Placing the heaters in the tree rows rather than in the centers of tree spaces also reduces the loss to the sky, as indicated by the example included at the bottom of Table 1, but the distribution of energy striking the trees is not as uniform because the heaters are so close to one side of the trees.

The experimental coke heater (fig. 7)

had the highest radiant fraction of the various kinds tested, while the Fugit was lowest. In general, the hot-stack or combustion-chamber type of heaters are better than other kinds of oil-burning heaters in regard to radiant energy output, because of the higher metal temperatures and the larger vertical surface areas from which radiation takes place.

Effect of heater placement. While the curves in figure 4 show the total amount of radiant energy received by the trees, they do not indicate the distribution between individual trees located at various distances from the heater. If one considers a single Jumbo Cone heater placed in the tree row between two trees (12 ft. diam. by 12 ft. high), 70 per cent of all the radiant energy received by the trees goes to the close sides of the two trees in the same row next to the heater. The nearest trees in the adjacent row on either side receive only 5 per cent each. Trees in the second row out receive practically no radiant energy.

Table 2.—Summary of Radiant Energy Outputs from Heaters

Kind of heater	Burning rate,* lbs./hr.	Radiant fractions, % of total fuel energy							Radiant fraction at lower burning rates
		Total from heater	12' x 12' trees			16' x 16' trees			
			to ground	to trees	to sky	to ground	to trees	to sky	
Heaters in centers of tree spaces (20' x 24' tree spacing)									
Exper. Coke....	5.4	41.7	13.6	13.3	14.8	13.0	20.3	8.4
Jumbo Cone....	5.6	29.6	10.7	9.8	9.1	9.3	15.4	4.9	less
Return-Stack..	5.4	27.6	9.8	8.9	8.9	8.7	14.1	4.8	slightly less
Kittle.....	5.7	27.5	12.0	8.6	6.9	10.6	13.8	3.1	less
Hy-Lo 230A....	4.4	22.2	8.0	7.1	7.1	7.7	10.8	3.7	slightly more
Fugit.....	8.1	18.1	8.8	4.4	4.9	8.5	6.8	2.8	slightly more
Heaters in tree row (trees 20' apart, rows 24' apart)									
Jumbo Cone....	5.6	29.6	10.1	13.4	6.1	less

* Calculations are for a particular test run at this burning rate. Radiant fractions remain about constant for burning rates above these values.

If the heater is placed in the center of the space between four trees, each of these four receives about 20 per cent of the total amount of radiant energy going to all trees. The next trees out receive only from 1 to 4 per cent each.

Figure 5 shows the radiant energy distribution for rows of Jumbo Cone heaters within a heated area. Both patterns show one heater per two trees in every row. At the left, the heaters are in the tree spaces, while at the right they are in the tree rows. The numbers below the diagrams indicate relative amounts of radiant energy received by all trees in any one row when all of the heaters are in operation or when only part of them are used.

The most uniform distribution is obtained when the heaters are in the spaces

and all heaters are burning. Each tree then receives equal amounts of radiation from two opposite sides. With only every other row burning *in the spaces*, all trees receive equal amounts, but concentrated on one side. With every other row burning *in the tree rows*, there is nearly a 3 to 1 variation between radiant energy received by heated rows and by intermediate rows.

When only every fourth row of heaters is used (one heater per 8 trees), the coldest rows receive very little radiant energy and hence must be heated almost entirely by convection. Fortunately, the use of such a small number of heaters is usually associated with conditions of moderate or large inversion when convective heat can be of some benefit.

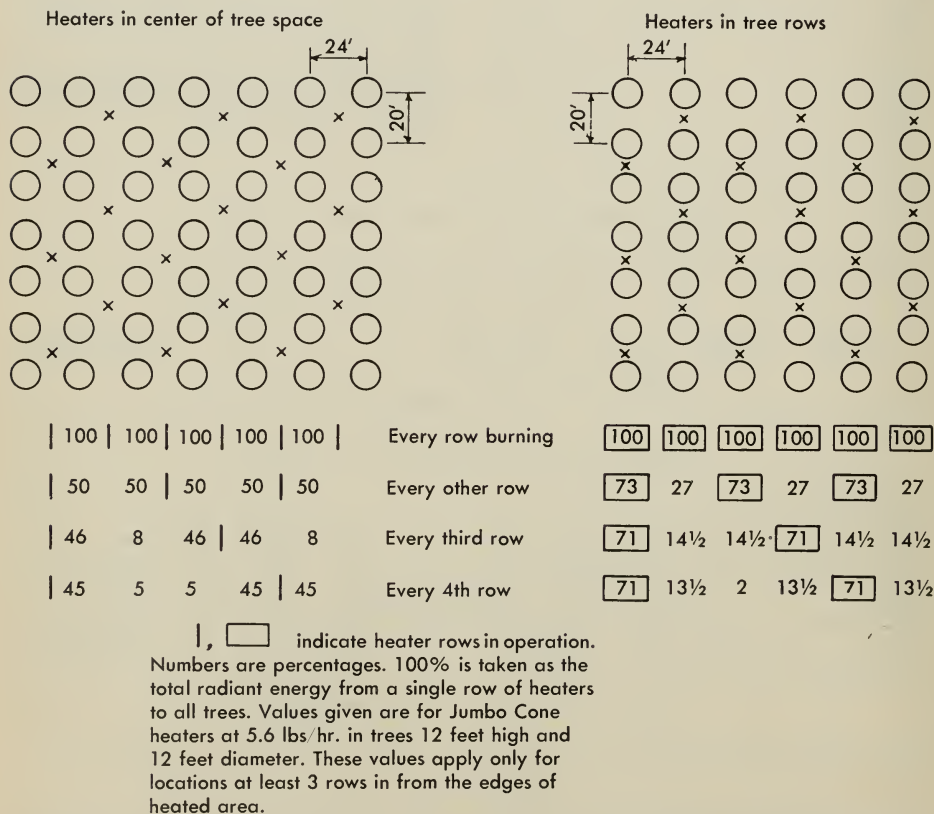


Fig. 5. This chart shows distribution of radiant energy from rows of heaters to rows of trees, for various heater spacings.

Tests in a one-acre plot—how they were set up and what the results indicated

In order to obtain an accurate comparison of the effectiveness of various types of heaters based upon many tests under carefully controlled operating conditions, a one-acre square plot within a larger orchard at the Citrus Experiment Station was instrumented and groups of heaters were operated in it under various conditions. Heating runs were made on approximately 55 nights during three winters. These runs were all made on nights not quite cold enough to require protection, but under typical radiation frost conditions. Temperature inversions ranged from 4 to 20° F.

Arrangements and kinds of heaters. Nine different kinds of heaters (illustrated in figs. 6, 7, and 9) were tested. They are as follows:

1. Hy-Lo 230A
2. Riverside Junior Louvre
3. Jumbo Cone
4. Exchange model, 7-inch stack
5. Experimental Return-Stack
6. Kittle
7. Fugit
8. Experimental coke
9. Experimental coke heater with radiation shields added

The experimental coke heaters were tested with radiation shields added, as well as without them, in order to compare the relative merits of convective heat and radiant heat under extreme conditions. Each shield (fig. 7) consisted of two concentric cylinders of galvanized iron, 3 feet tall, open at both ends, and held above the ground about 4 inches to allow the entrance of air. The clearance between the inner and outer cylinders was about 4 inches. The coke heaters were placed inside of these shields.

With the shields in place, the radiant fraction to the trees was only about one per cent of the total fuel energy, because the shields confined the radiant energy and caused it to be used in heating air

which circulated up within the shields. Thus when the shields were used the coke heaters became almost 100 per cent convective heaters, while with the shields removed these heaters had the highest radiant fraction of any heaters tested.

In general, heaters in the one-acre plot were placed in the centers of the tree spaces, with one heater per two trees within the plot. Border heaters were spaced one per tree on all four sides, giving a total of about 70 heaters for the entire heated plot. A few tests were made with Fugit heaters spaced one per three trees within the plot, but still with one per tree on the upwind borders.

Test set-up and procedure. Temperatures from thermocouples at many locations in the heated plot (fig. 8), and in a similar upwind, unheated area, were recorded automatically at 10-minute intervals. The usual heating period during a run was about 3 hours. Temperatures were generally recorded for a 2-hour period just before lighting heaters, in order to establish natural differences between temperatures in the two plots.

For determining the responses or heating effects from different kinds of heaters, the 5-foot air temperatures at the centers of 4 adjacent trees in the middle of the heated plot were averaged and compared with corresponding temperatures in the unheated check plot. In addition, vertical profiles of temperatures taken near the center of the heated plot were compared with similar temperatures in the unheated plot.

During some of the runs, leaf and fruit temperatures were measured in addition to air temperatures. While these temperatures are the critical ones to consider in determining the amount of protection required during dangerous periods, they may vary several degrees for different exposures and locations on the tree. For example, fruit exposed directly to heater

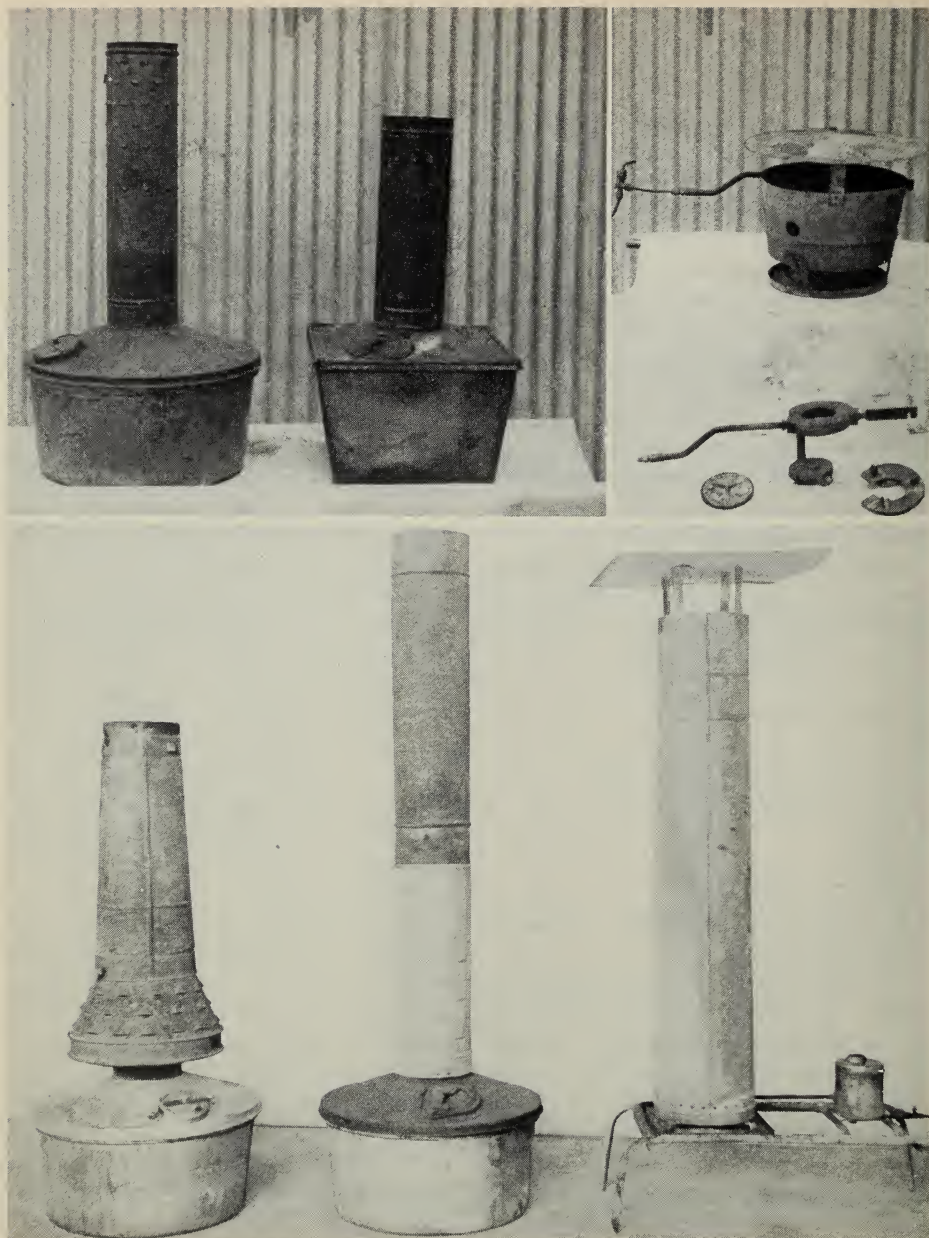


Fig. 6. Types of commercially available heaters tested. Upper left to right: Hy-Lo 230A (24-inch stack); Riverside Junior Louvre (18-inch stack); Fugit (1937 model) with generator parts shown. Lower left to right: Jumbo Cone; 7-inch Exchange Model; Kittle.

radiation will be warmer than the air, while fruit on the "dark" side of a tree and exposed to the sky will be colder than the air. Since heat transfer to or from the air tends to average out variations be-

tween individual fruits and leaves, air temperatures were used for all heater comparisons.

The total amount of fuel consumed during each run was determined by

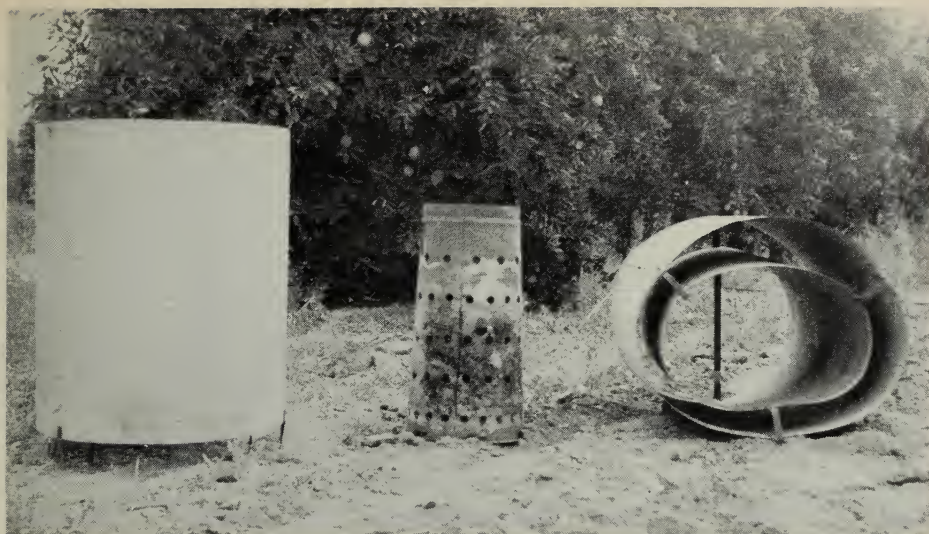


Fig. 7. Experimental coke heater (center). On either side are views of the radiation shields used in studies. Without shields this heater had a high radiant fraction; with shields, practically none.

weighing the heaters individually before and after the run, using a specially designed portable scale unit (fig. 9). Only one kind of heater was tested in the main plot during any particular night. However, occasional runs with the Hy-Lo 230A heaters were made during each of

the several winters of the study, as a check against possible changes in results from season to season. The results obtained with this heater were remarkably consistent from year to year.

Vertical profiles of heating response. Figures 10 and 11 show the



Fig. 8. Photo of the network of wires for thermocouples and other instruments in the one-acre plot at Riverside. Photo was taken during first year of tests; the trees were much larger by the end of the five-year period during which the tests were conducted.



Fig. 9. Portable unit used for weighing the heaters. With this equipment, one man could weigh and record 70 heaters in about 20 minutes. Heater on scales is the Experimental Return-Stack.

temperatures and response from heaters in relation to the height above the ground. Figure 10 represents a night with a rather small inversion (6° F warmer at 60 feet than at 5 feet), while figure 11 is for a large inversion (16° F). In each case the graph at the left indicates air temperatures up through the tree space and through the tree center, for both heated and unheated plots. The graph at the right shows heating effects at different elevations, as determined by the differences between the heated and unheated curves.

Note that during each night there was no measurable heating effect above 60 feet. In each case the air in the tree tops (as shown by the dotted curves at 10 to

12 feet elevation) was colder than air at the same height between trees. This is due to the loss of heat by radiation to the sky from the relatively large tree-top area. Near the ground the air is warmer within the trees than in the space between the trees because the soil under the trees is warmer, being protected from sky radiation. Both graphs illustrate the phenomenon of the coldest air being at 2 to 5 feet above the ground, as explained on page 5.

Relative effectiveness of different heaters. For direct comparison of the results from the various kinds of heaters, the average 5-foot tree-center heating effects for the individual test runs were adjusted by proportion so that they would

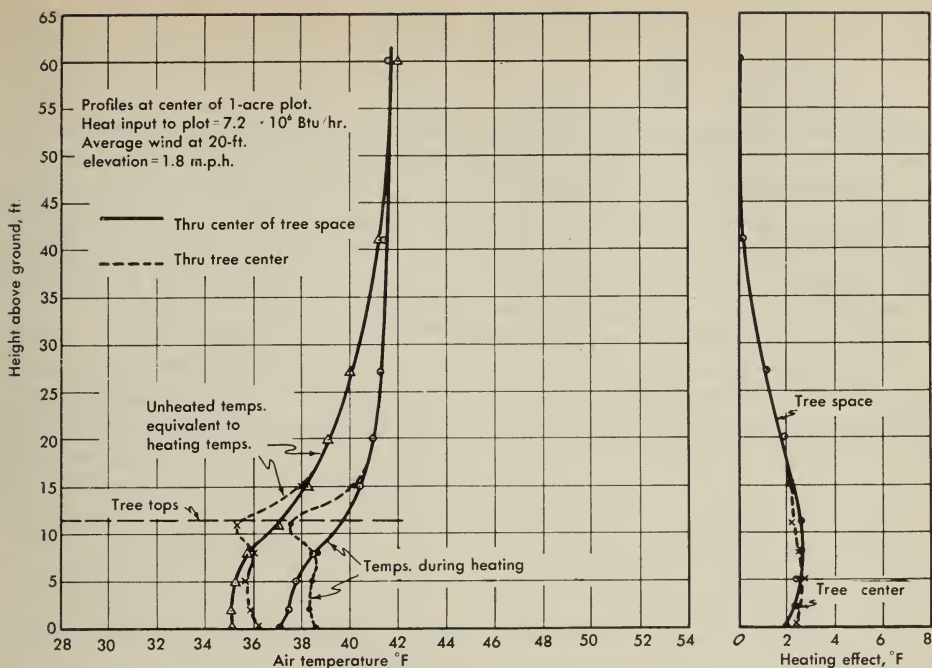


Fig. 10. Vertical profiles of temperature and heating effects at center of one-acre plot, for a night with a small inversion. Hy-Lo 230A heaters were used in the plot during this test.

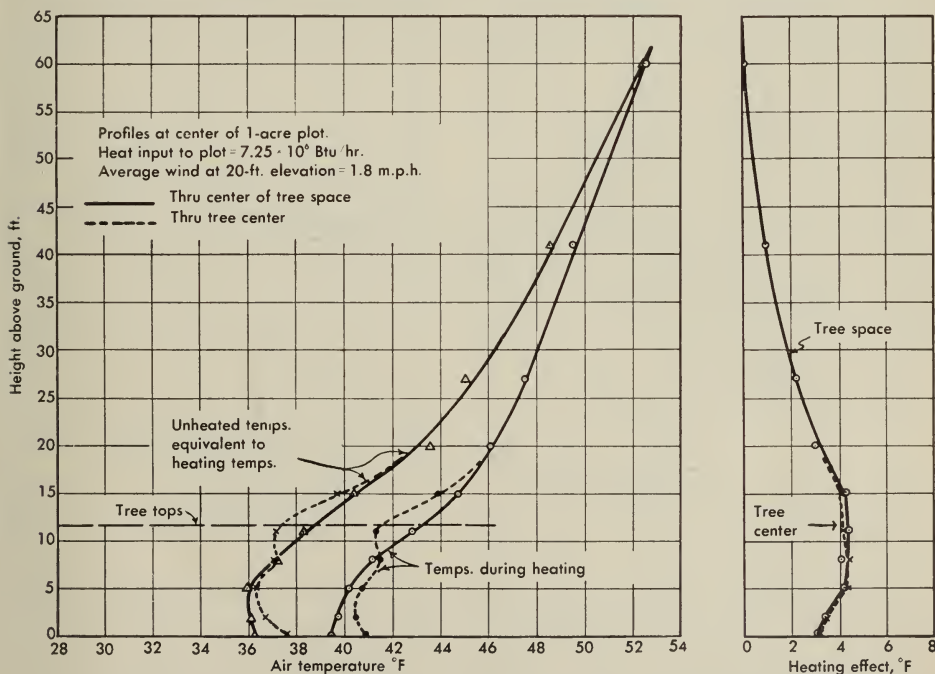


Fig. 11. Vertical profiles of temperature and heating effects at center of a one-acre plot, for a night with a large inversion. Return-Stack heaters were used in the plot during this test.

all represent the same fuel input to the plot (50 gallons of oil per hour, or an equivalent amount of coke).

Figure 12 shows curves of heating effect in relation to temperature inversion for the different kinds of heaters tested. The experimental points representing individual runs have been omitted from the graph. Each curve, however, is based upon at least 3 runs at different inversions. The results from 11 of the 55 nights were not used because of periods with wind or unsteady conditions during the tests. Of the 44 runs used in plotting these curves, only 4 were more than 10 per cent above or below the curves as drawn.

The curves of figure 12 confirm field experience that regardless of the kind of heater, the response for a given fuel input is less for small inversions than for larger ones. When the inversion is large, there appears to be little choice as to type of heater, but at the smaller inversions there are definite differences in effectiveness. At 6° F inversion, for example, the re-

sponse with Fugit heaters spaced one per 3 trees was only half as great as with coke heaters for the same heat input in the plot. Of the bowl-type heaters tested, the lazy-flame heaters were the least effective at small inversions, while the Jumbo Cone and 7-inch Exchange heaters appeared to be the best. At inversions smaller than those included on the curves, the differences between heaters would undoubtedly be greater.

If values of heating effect are taken from figure 12 for the various heaters at a small inversion (5° F), and values for radiant fractions to trees plus ground are taken from figure 4 for the appropriate burning rates, it can be shown that the effectiveness or response of the various heaters at this inversion was in almost direct proportion to the radiant fractions.

Taking the extreme comparison of coke heaters with and without radiation shields, figure 12 indicates that even at an inversion as large as 10° F, the shielded heaters (with practically no radiant energy output) gave less than 40

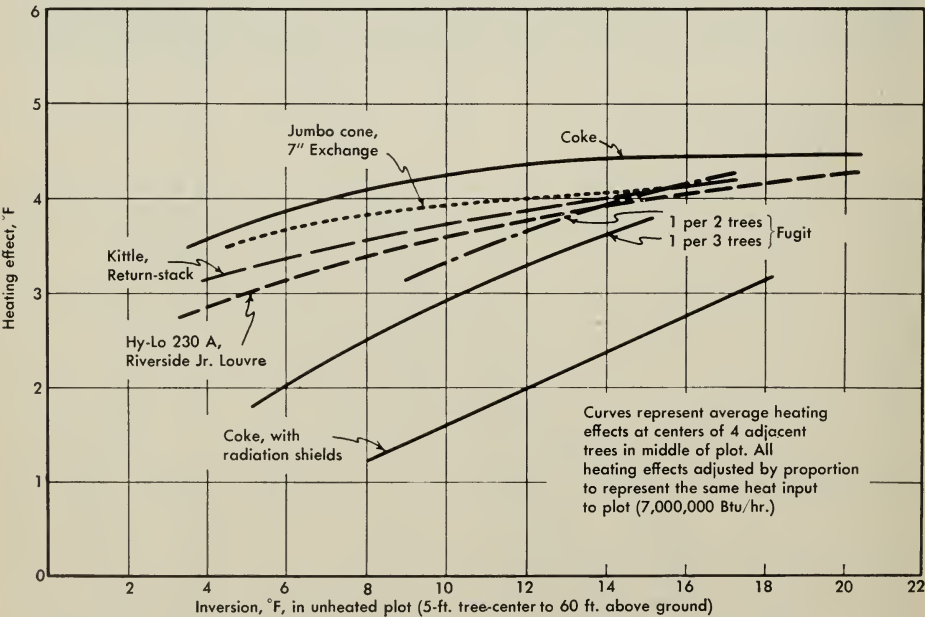


Fig. 12. This graph shows the effect of temperature inversion, and kind of heater used, upon heating response measured at the center of the one-acre plot.

per cent as great a response as did the same heaters with shields removed (high radiant output). However, when the inversion was 17°, the response with the shielded heaters was 65 per cent as great as that with the unshielded heaters. It is probable that at an extreme inversion of 22 to 25° F, there would be little difference in the heating response with or without shields.

In other words, when the inversion is small, most of the convective heat (hot stack gases and heated air) rises above the tree tops and is lost. Under these conditions, radiant heating must be the principal means of protection. With a large inversion more of the hot gases are held down within the tree zone to supplement

the effect of radiant heat. Therefore, the smaller the inversion, the more advantage there is in using heaters with high radiant fractions.

These heater comparisons were made only in a one-acre plot, with responses being about half as great as might be expected in mass heating. The one-acre results can, however, be applied directly to the outer portions of a larger heated area, since the response seems to be pretty much a function of the distance in from the edge regardless of the total size of the area (see page 26). Within the center portion of a large heated area there might not be as much difference between kinds of heaters, but they should still rank in the same order in regard to effectiveness.

Tests in isolated orchards indicate need for special attention to border heating

Five test runs were made with heated areas ranging in size from 7 to 28 acres. Of these, the two made in a 15-acre plot at the Citrus Experiment Station were by far the most complete in regard to instrumentation and results. Since these runs were made during nights not quite cold enough to actually require protection, it was possible to control the tests as desired and to install an adequate number of thermocouples in advance.

The one run at Porterville and the two at West Covina were made during nights when there was general heating but not in areas adjacent to the test orchard. In each case, portable equipment was taken from Riverside and set up in the orchard just a few hours prior to the start of heating, after it appeared reasonably certain that firing would be required.

All of these tests were in orange orchards with trees about 15 feet in diameter and 15 feet high, planted on either 22 × 22 or 20 × 24-foot centers. In each case, the heaters were placed in the tree rows with one heater per two trees within

the orchard. In some cases, however, only part of the heaters were lighted.

Fifteen-acre area at Riverside.

During two nights in March, 1941, when minimum temperatures were about 35° F, a 15-acre square plot was heated, using all of the 45 heaters per acre within the area. During the last half of the 4-hour heating period on each night, the upwind border was increased from one heater per 2 trees to one heater per tree. On the other 3 sides, the regular spacing of one per 2 trees was maintained. Most of the heaters were equipped with 7-inch Exchange stacks, and the average burning rate on each night was about ¾ gallons per hour per heater.

Thermocouples were placed at the centers of various trees along the middle row across the plot to obtain heating effects at various distances in from the edge of the heated area. The permanently instrumented plot used for one-acre studies served as the unheated check station for these tests. In addition to the tree-center temperatures, vertical tem-

perature profiles were measured in the unheated plot and at the center of the heated area. Two captive balloons, operated simultaneously at these two locations, were used to obtain temperatures above the height of the thermocouples mounted on poles.

Figures 13 and 14 show vertical temperature profiles up to 300 feet for the two nights. The difference between the heated and unheated curves is shown at the right on each graph and represents the heating response. For the night with 14° F inversion (fig. 13), the graph indicates practically no heating effect above 50 feet; while on the night with only 7.5° F inversion (fig. 14), there was a definite response up to 100 feet but none above that elevation. When the inversion is small, there is less heating effect within the tree zone than with larger inversions, but heating extends to a higher elevation as shown by these graphs because the hot stack gases and warmed air rise more readily and must go higher before their temperature reaches the same value as that of the surrounding air. For instance, in figure 14 the air in the heated orchard at 30 feet was warmer (and hence lighter) than the unheated air at 100 feet; thus it would continue to rise until further cooling could bring about a balance of densities.

Figure 15 shows the variation of 5-foot tree-center heating effects across the heated area. The 20-foot air drift during these tests was 1½ to 2 miles per hour and was consistently from east to west (from left to right on the graphs). The top graph contains two curves—one for the night with 7.5° F inversion and one for 14° F. The tree-center responses throughout the heated area were 15 to 20 per cent less on the night with the smaller inversion. In both cases, the heating effects obtained in the center portion of the area were about as large as can normally be obtained in general heating practice.

During each of the two runs, the heating effect at the upwind edge was only

about 40 per cent as great as in the center portion, gradually increasing toward the center of the plot and then decreasing again beyond the center, although on the *downwind* side. Obviously the increase in heating effect from the upwind edge toward the center is due at least in part to the progressive accumulation of heat as the natural air drift carries the incoming air past more and more heaters.

It might be expected that the heating effect would continue to increase in this manner nearly to the downwind edge of the plot, but as indicated in figure 15 this was not the case. The response gradually decreased in the last ten or twelve rows and at the downwind edge was only 60 per cent as great as in the center portion. When a sensitive wind vane was placed at the downwind edge about 3 feet above the ground, it indicated a definite movement of air into the orchard at this height, *directly against the prevailing air drift*.

Some indication of the vertical depth of this indraft may be obtained from results for a few one-acre runs when vertical temperature profiles were measured in the second tree-row from the downwind edge, as well as at the center of the plot. Composite results for 6 nights whose average inversion was 6° F show that throughout the lower 20 feet of elevation, the heating effect at the downwind edge was about 15 per cent less than at the center of the plot; while above 25 feet there was no difference between the two locations. Six other nights with an average inversion of 14° F had 25 per cent less heating effect near the downwind edge in the lower 15 feet and showed no difference above 20 feet.

Thus for an isolated orchard, the rising stack gases and heated air create an up-draft which draws in cold air from all sides of the plot, at least if the prevailing natural drift is small. Reduced re-radiation from the overhead heated gases, to the orchard near the edges of the heated area, may also contribute to the lesser

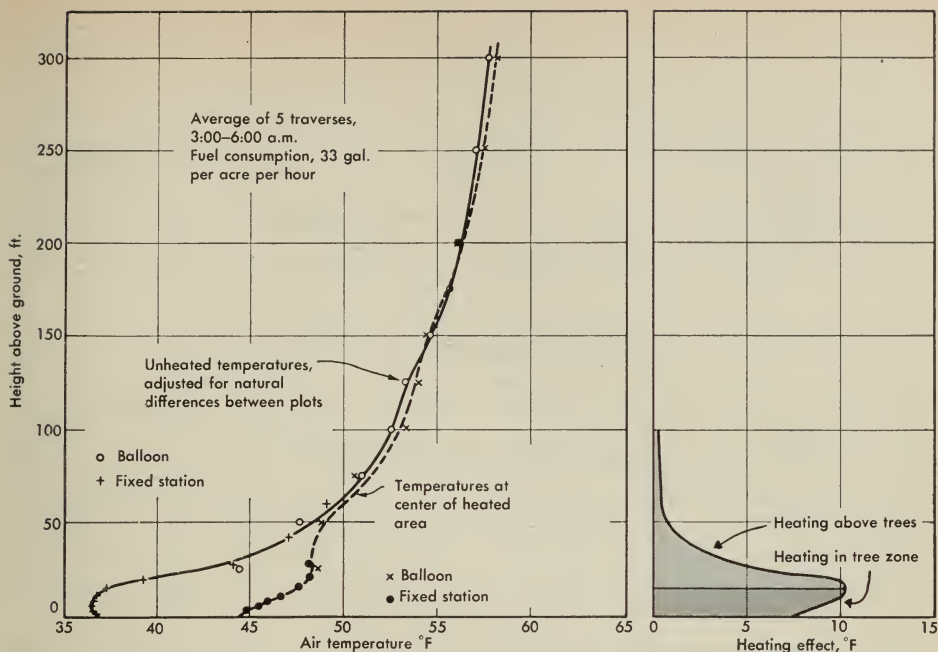


Fig. 13. Vertical profiles of temperature and heating effect in the center portion of a 15-acre heated area. Test was made during a night on which there was a large inversion.

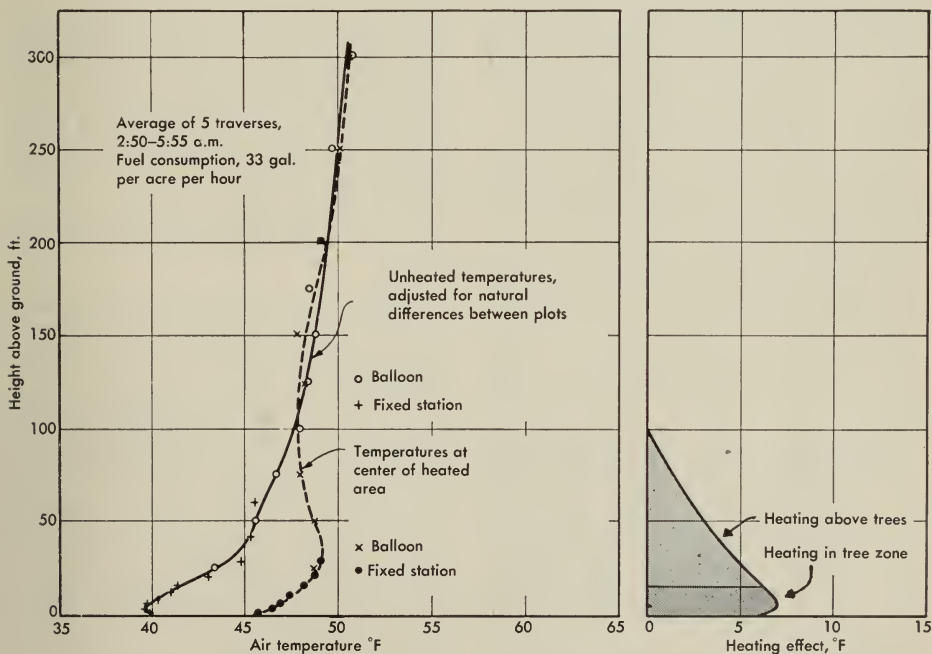


Fig. 14. Vertical profiles of temperature and heating effect in center portion of a 15-acre heated area. This test was made on a night during which there was a moderately small inversion.

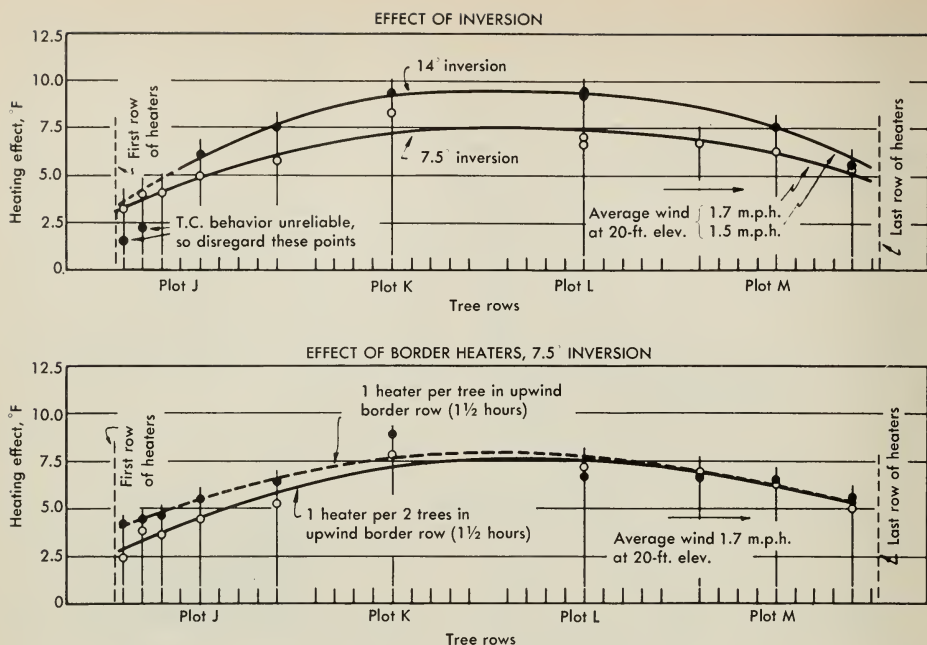


Fig. 15. These graphs show tree-center heating effects in the middle row, across a 15-acre heated area. Average burning rate was 0.75 gallons per hour per heater, using 45 heaters per acre. These results do not include the lighting period.

response. Regardless of the cause of the reduced heating effect, it is evident that extra border heaters are needed on all sides of an isolated orchard, although in greatest numbers on the upwind side.

The bottom graph in figure 15 indicates that when the number of heaters on the upwind border was doubled (to one heater per tree), the response increased by about 50 per cent at the edge, and by lesser amounts throughout the upwind 10 or 12 rows. No tests were run with heavier border concentrations or with extra heaters on the downwind or side borders.

Seven-acre area at Porterville.

On the night of December 14-15, 1940, when general heating was necessary in the Tulare district, portable equipment from Riverside was set up and operated in a 7-acre heated tract northwest of Porterville. The heated area was part of a larger unheated orchard which extended upwind from the heated portion, providing a good location for an un-

heated check station. In the heated area, temperatures were measured only at the center of the plot. At both the heated and unheated stations, 5-foot tree-center temperatures were measured in order to determine average heating effects, and fixed thermocouples were mounted at elevations up to 28 feet on portable poles. A captive balloon was operated at the heated station.

Within the plot, lazy-flame heaters were spaced one per two trees, while on all four sides of the heated area the spacing of border heaters was one per tree. Starting at 11:30 p.m. all of the border heaters and every other row of the heaters within the plot were lighted. At about 3:30 a.m. the remainder of the heaters were lighted, and heating continued until about 7:30 a.m. Figure 16 shows the heated and unheated tree-center temperatures during the night, as well as the 60-foot temperatures and the 20-foot wind velocities. During the first heating period, the average response was 4.1° F; with all heaters

burning, it was 8.8° F. The average burning rate was 0.7 gallons per hour, and the temperature inversion was 13° F.

The average vertical temperature profiles obtained between 3:00 and 6:00 a.m. during this run are not shown. However, they were similar in shape to the ones for the Riverside run with similar inversion (fig. 13) but with temperatures 12 to 14° F colder at all heights up to the 300-foot limit of the readings. There was no indicated heating effect above 100 feet and very little above 50 feet.

Twenty-eight acre area at West Covina. Two runs were made in an isolated orange orchard near West Covina on nights when light or moderate general firing was required. The terrain at this location is very flat, since the orchard is located on the floor of a valley. Even so, the average 20-foot wind velocity during the two nights was 1 to 1½ miles per hour. Since there was no adjacent orchard, it was necessary to locate the unheated check station in a bare, plowed field.

In addition to the regular heater spacing of one per 2 trees within the orchard,

there was a border row along the northeast side with one heater per tree. The southwest border had a few extra heaters, but the other two had only the regular spacing. On the night of January 2-3, 1942, all of the border heaters and every fourth row within the plot were burned from 1:30 a.m. to 8:00 a.m. During the night of February 14-15, the first heaters were lighted at about 1:00 a.m., following the same pattern as for January 3. Additional heaters were lighted at 4:00 a.m. and still more at 6:30 a.m., as indicated in the upper part of figure 17. After 6:30 a.m., all of the odd-numbered rows of heaters within the orchard were burning, in addition to the borders. For both nights the average heater burning rate was about 0.5 gallons per hour.

The average inversion was 8° F on the first night and 5.5° F on the second night. Vertical temperature profiles (not shown) indicated no response above 100 feet on either night. The lower part of figure 17 shows, for the second night, the tree-center heating effects at various distances in from the northeast edge of the orchard. Although this was the side with a border

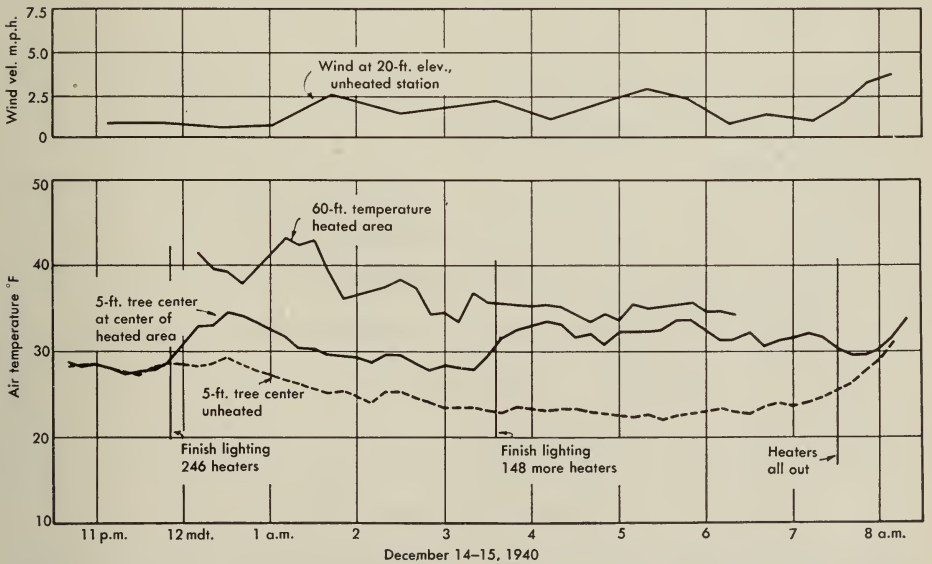


Fig. 16. These curves show wind velocity and air temperatures in a 7-acre heated plot at Porterville, California, during the night of December 14-15, 1940.

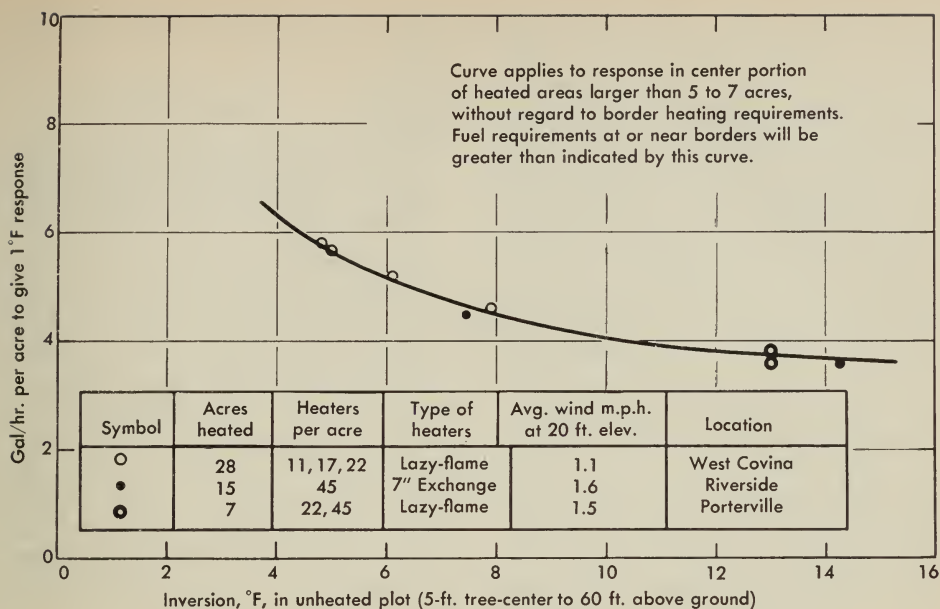


Fig. 18. This shows the effect of temperature inversion on fuel requirements per degree of response, in the center portion of 7- to 28-acre heated areas.

of one heater per tree, the drift entered from this direction during only about one-third of the time; usually the drift was more nearly parallel with this border. The three curves represent the three periods during which different numbers of heaters were burning.

The heating effects indicated in figure 17 were measured in a row next to one in which heaters were burning during the entire time. These results indicate a nearly uniform response in this row when only every fourth row of heaters was burning. As the number of heaters was increased, the difference between the center response and that near the edge increased, perhaps because of additional indraft caused by the stronger orchard stack action with more heaters. The response in the outside row was greater, presumably because of the nearly parallel wind and the direct heating by radiation from the heavy row of border heaters, while the indraft of cold air flowed past these trees and prevented the next trees in from being warmed as much.

Tree-center temperatures during both of the nights indicated that when only every fourth row of heaters was burning, trees in the three cold rows each had about 25 per cent less response (0.3°F less) than trees in a row containing lighted heaters.

Relation of response to size of heated area. The effect of temperature inversion upon fuel requirements per degree of response at the centers of the 7-acre, 15-acre, and 28-acre orchards is shown in figure 18. The fuel inputs in gallons per hour per acre were based upon the average heater spacing within the plot, without regard to border heaters. Where the number of heaters used per acre was changed during a particular run, separate points were plotted for each period. During one of the runs at West Covina there were 3 such periods with increasing numbers of heaters in operation, while at Porterville there were 2.

Although the actual fuel inputs for different runs varied from 6 to 34 gallons per hour per acre, and the plots were in

3 different localities with sizes ranging from 7 to 28 acres, the results fit a single curve rather closely. This indicates that in the center portion of a heated area, beyond the influence of border conditions, the response is relatively independent of the size of the area heated. The curve indicates a considerable increase in fuel requirements as the inversion decreases below 12 to 14° F. For example, the fuel requirements at an inversion of 4° F would be 50 per cent greater than at 10° F.

In tests with the 15-acre plot (fig. 15) the reduced response due to border effects extended in 10 to 15 rows from the edge. The responses were about constant throughout the center portion of the orchard and were about as large as are normally expected even in mass heating. Thus, although the largest heated area involved in these tests was 28 acres, it is probable that the fuel requirements indicated by figure 18 would apply to larger areas on reasonably flat terrain.

The rule used by some growers, that they normally will need to light 8 heaters per acre to obtain a response of about 1° F, is consistent with the fuel requirements indicated by the curve for an inversion of 10° F (assuming a burning rate of 1½ gallon per hour). The curve in figure 18, however, should not be used for areas of less than 6 to 8 acres, because the reduced response due to border effects is likely to extend in to the center of areas smaller than this limit.

Regardless of the size of heated area, the fuel requirements near the edges will be greater than those indicated in figure 18 for the center portion. Conversely, if heaters are uniformly spaced, with no extras on the borders, the response near the edges of the orchard will be less than in the center. The magnitude of this reduction of border response is influenced considerably by the total rate of fuel consumption per acre per hour. For example, in 3 runs with heater spacings of 11, 22, and 45 per acre, in 15-acre or 28-acre

orchards, the following results were obtained:

Total fuel rate, gallons per acre per hour	Response at third tree in from upwind edge
5.5	90% as great as in center of area
11.0	70% as great as in center of area
33.7	50% as great as in center of area

The greater reduction in border response with larger fuel inputs appears to be largely a result of greater inflow of cold air due to the increased updraft created by the heaters. Within a large heated area (beyond border influences) the tree-center response is limited by increased radiation to the sky from the warmer trees and air, and by reduced outflow of heat from the soil as its surface temperature rises (decreasing the temperature *difference* between the soil surface and the lower depths).

Results obtained from comparable tests with the different sizes of heated areas indicate that the response at a given distance in from the upwind edge (but not beyond the center) is about the same regardless of the size of the plot. For example, with 7-inch exchange heaters and similar conditions, the tree-center heating effect at the fifth row in from the upwind side of the one-acre plot (at center of plot) was almost as great as in the 15-acre plot at the same distance in. Likewise, the response obtained near the center of the 7-acre orchard at Porterville (12 rows in) agrees quite well with results obtained in the 15-acre plot.

Since the response appears to be a function of the distance in from the edge, the extensive results obtained in the one-acre plot regarding responses and relative effectiveness of different kinds of heaters should be directly applicable to a strip around the outside of a larger isolated orchard. The importance of border considerations becomes more apparent when one considers that with 90 trees per acre, a strip only 5 trees wide all around a 15-acre area, or 7 trees wide around 30 acres, represents half of the orchard.

From the tests, border heating recommendations can be made for isolated orchards

While the tests did not include enough large-plot runs to actually check the best arrangement of border heaters for a uniform response, sufficient information is available to serve as a basis for recommendations in this respect. The following general considerations should be kept in mind in regard to border heaters:

(a) High radiant output from the heaters is especially important in border areas, so that the outside trees may be heated directly, without the necessity for warming all of the inflowing air before it gets into the orchard. If a grower has more than one kind of heaters, those with highest radiant fractions should be used on the borders.

(b) Border heaters should be distributed

over the first two or three rows in and not be all concentrated on the outside. This will allow a greater percentage of the tree surfaces in the outer rows to be "seen" by the heaters and thus be heated directly by radiation.

(c) Avoid excessive burning rates for border heaters; use larger numbers of properly distributed heaters at normal burning rates. In the center portion of the orchard, burning rates should be kept as low as possible to minimize updraft which draws in cold air along the borders.

(d) Border heaters are usually needed on all sides of an isolated heated area but with greatest numbers on the upwind side. Never use less than one heater per two trees on any outside edge.

**FOR OUTSIDE AND PERHAPS FIRST ROW IN
ON ALL SIDES EXCEPT UPWIND SIDE, USE
TWICE AS MANY HEATERS AS USED WITHIN THE PLOT**

**ALONG UPWIND EDGE,
USE 4 TIMES AS MANY
HEATERS AS USED WITHIN
THE PLOT (BUT NEVER
MORE THAN 2 HEATERS
PER TREE)**

**PREVAILING
AIR DRIFT** →

**IN THESE TWO ROWS,
USE TWICE AS MANY
HEATERS AS USED
WITHIN THE PLOT**

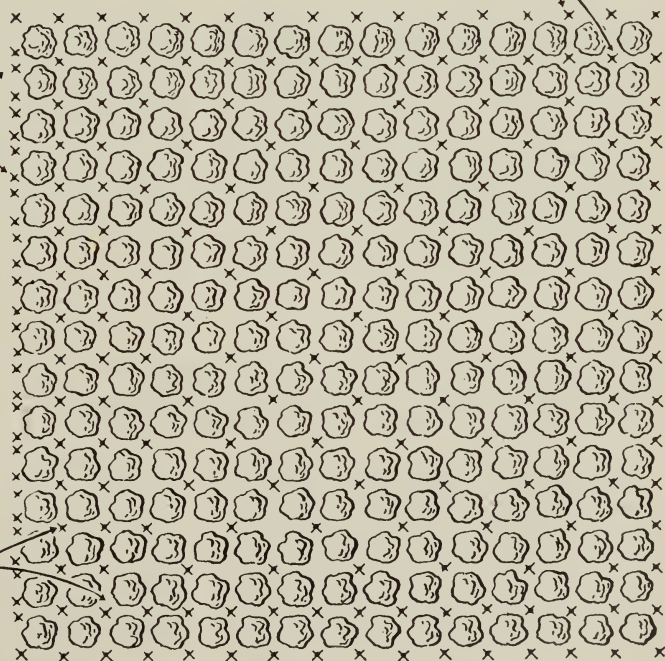


Fig. 19. Typical example of border heater spacing, when using one heater per two trees within the orchard. Small crosses indicate heaters.

The actual border heating requirements will vary considerably, depending upon the topography, the wind velocity, the intensity of the heating (gallons per hour per acre), the temperature inversion, and other factors. However, for the usual conditions with reasonably flat terrain and low wind velocity, the following spacings are recommended:

(a) Upwind borders. On the outside of the orchard, use four times as many heaters per tree as are used within the orchard. For the first two rows in from the edge, use twice as many as are used within the orchard. Never use more than two heaters per tree on the outside nor less than one heater per two trees on the outside and the first row in.

(b) Downwind and side borders. On the outside and perhaps for the first row in, use twice as many heaters per tree as are used within the orchard. Never use less than one per two trees on the outside.

Examples:

(1) Suppose the required response is small so that only one heater per 8 trees is needed within the orchard. Then all borders should have the minimum of one heater per two trees on the outside. In addition, the first row in from the upwind side should have the minimum of one per two trees.

(2) Assume that one heater per two

trees is needed within the orchard. Then on the upwind side use two heaters per tree on the outside and one heater per tree for the first two rows in. On all other sides, use one heater per tree on the outside and perhaps for the first row in. (See fig. 19.)

Use of heaters with wind machines. Recent tests and field experience indicate that the combination of wind machines with uniformly distributed heaters gives a response greater than the sum of the normal response from the heaters alone plus the response from the wind machine alone.

In tests during two nights at the Citrus Experiment Station at Riverside during February, 1950, the combined response from a 90-horsepower wind machine, plus 15 heaters per acre, was 20 to 30 per cent greater than the sum of the individual responses.*

Within the zone of disturbance, the air mixing caused by the wind machines tends to make the convective heat from the heaters more useful than when heaters alone are used. However, beyond this zone of influence, such as in the corners of a square orchard, the heaters must do the entire job, and the radiant output is fully as important as for border heaters in an orchard heated in the conventional manner.

The findings and recommendations apply only indirectly to large-scale heating operations

In the so-called mass heating of large areas, the fuel requirements within the heated district will probably be a little lower than indicated by figure 18. As previously discussed, these large-area fuel requirements are determined primarily by the heat input required to counteract the normal radiation losses, plus the additional losses resulting from

the higher temperatures of the trees, air, and soil surface in the heated orchard.

For large-scale heating, the border effects are confined mainly to the orchards on the outer fringes of the heated district. However, if an orchard well

* Frost Protection by Combining Wind Machine with Distributed Heaters, by F. A. Brooks, D. C. Rhoades and H. B. Schultz, *California Agriculture*, Vol. 4, No. 9, Sept. 1950.

within a heated district does not have other heated areas reasonably close, it will probably need some extra border heaters.

As with borders and isolated orchards,

the use of heaters with high radiant energy outputs will give somewhat better response for mass heating, particularly when the inversion is small and heating requirements are severe.

And here is a summary of the findings that resulted from the orchard heating tests

The principal factors which affect the amount of fuel required for a given temperature response are:

1. Magnitude of temperature inversion. Heating is most difficult on nights with small inversions or so-called high ceiling.
2. Inflow of cold air, due either to natural drift or to the combined stack action created by the heaters in an isolated orchard. In the heating of large areas, the effect of inflow diminishes, except for border orchards.
3. Heater characteristics, particularly in regard to radiant energy. With a small inversion the convective heat is largely wasted above the tree tops and radiant heat thus becomes the principal means of protection.

In the one-acre heating studies, when the inversion was large, there was little difference between the various kinds of heaters in regard to effectiveness. When the inversion was small, however, the effectiveness was directly related to the radiant fractions of the heaters. The several kinds of heaters which were tested may be rated in the following order in regard to heating effectiveness or response for a given fuel energy input:

1. Experimental coke
- 2, 3. Jumbo Cone and 7-inch Exchange stack (no difference)
- 4, 5. Return-Stack and Kittle (no difference)
- 6, 7. Hy-Lo 230A and Riverside Junior Louvre (no difference)
8. Fugit (one heater per two trees)
9. Fugit (one heater per three trees)

Five test runs were made in isolated orchards ranging in size from 7 to 28 acres with inversions of from 5 to 14° F and with fuel inputs from 6 to 34 gallons per acre per hour. Fuel requirements for a given tree-center response within the center portions of the areas were consistent for all of these tests, and indicate a definite increase as the inversion becomes smaller. In none of the tests was there any measurable response at heights greater than 100 feet above the ground. With fairly large inversions, the heating effect was confined mostly to the lower 50 feet, while with small inversions there was considerable heating between 50 and 100 feet (practically useless to the orchard).

A definite orchard stack action, created by the rising of the heated air and gases from all the heaters, was observed and is indicated by the test results. Cold air apparently is drawn in from all sides of an isolated heated area, with the depth of inflow probably being as great as the tree height, even on the downwind side.

The combined effect of the natural air drift and the inflow of cold air caused by this orchard stack action is to reduce the response for as much as 10 to 15 rows in from the edges. The degree of reduction of border response is greatest for high rates of fuel input per acre because of the increased orchard stack action and indraft. Thus it is important to operate the heaters, especially those within the plot, at the lowest rates which will give adequate protection.

Border heaters should be distributed over the first two or three rows in, and not be all concentrated on the outside of the orchard. Heaters with high radiant output are especially advantageous in border heating. Border heaters are needed on all sides of an isolated orchard but with greatest numbers on the upwind side.

When heaters are used in combination

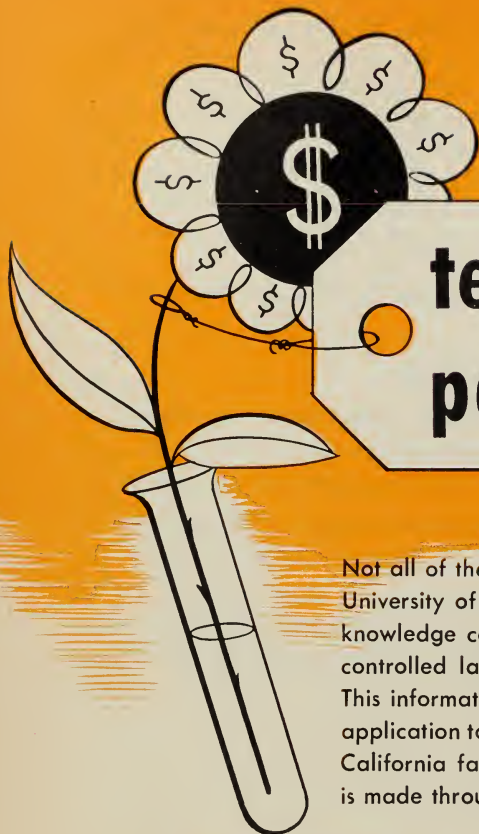
with wind machines, extra response is obtained because the convective heat from the heaters is made more useful by the mixing action of the wind machine. However, heaters beyond the zone of disturbance of the machine must do the entire job, and the radiant output is fully as important as for border heaters in an orchard heated in the conventional manner.

ACKNOWLEDGMENTS

A project as extensive as the one discussed in this publication involves the combined efforts of a considerable number of persons.

Staff members in addition to the author who were actively engaged in the field work on orchard heating during the period from 1937-1942 included the following: C. E. Barbee, L. M. K. Boelter, F. A. Brooks, C. Lorenzen, F. L. Rhinehart, and H. B. Walker.

The co-operation of the Citrus Experiment Station, particularly the Purchasing Department and the Division of Cultivations, was an invaluable aid during these studies.

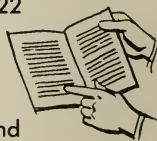


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